METHOD AND APPARATUS FOR CODING INFORMATION, METHOD AND APPARATUS FOR DECODING CODED INFORMATION, METHOD OF FABRICATING A RECORDING MEDIUM, THE RECORDING MEDIUM AND MODULATED SIGNAL

FIELD OF THE INVENTION

The present invention relates to coding information, and more particularly, to a method and apparatus for coding information having improved information density. The present invention further relates to producing a modulated signal from the coded information, producing a recording medium from the coded information, and the recording medium itself. The present invention still further relates to a method and apparatus for decoding coded information, and decoding coded information from a modulated signal and/or a recording medium.

BACKGROUND OF THE INVENTION

When data is transmitted through a transmission line or recorded onto a recording medium such as a magnetic disc, an optical disc or a magneto-optical disc, the data is modulated into code matching the transmission line or the recording medium prior to the transmission or recording.

Run length limited codes, generically designated as (d, k) codes, have been widely and successfully applied in modern magnetic and optical recording systems. Such codes, and means for implementing such codes are described by K. A. Schouhamer Immink in the book entitled "Codes for Mass Data Storage Systems" (ISBN 90-74249-23-X , 1999). Run length limited codes are extensions of earlier non return to zero recording codes, where binary recorded "zeros" are represented by no (magnetic flux) change in the recording medium, while binary "ones" are represented by transitions from one direction of recorded flux to the opposite direction.

In a (d, k) code, the above recording rules are maintained with the additional constraints that at least d "zeros" are recorded between successive "ones", and no more than k "zeros" are recorded between successive "ones". The

first constraint arises to obviate intersymbol interference occurring because of puls crowding of th reproduced transitions when a series of "ones" are contiguously recorded. The second constraint arises to ensure recovering a clock from the reproduced data by "locking" a phase locked loop to the reproduced transitions. If there is too long an unbroken string of contiguous "zeros" with no interspersed "ones", the clock regenerating phase-locked-loop will fall out of synchronism. In, for example, a (1,7) code there is at least one "zero" between recorded "ones", and there are no more than seven recorded contiguous "zeros" between recorded "ones".

The series of encoded bits is converted, via a modulo-2 integration operation, to a corresponding modulated signal formed by bit cells having a high or low signal value. A "one" bit is represented in the modulated signal by a change from a high to a low signal value or vice versa, and a "zero" bit is represented by the lack of change in the modulated signal.

The information conveying efficiency of such codes is typically expressed as a rate, which is the quotient of the number of bits (m) in the information word to the number of bits (n) in the code word (i.e., m/n). The theoretical maximum rate of a code, given values of d and k, is called the Shannon capacity. FIGURE 1 tabulates the Shannon capacity C(d,k) for d=1 versus k. As shown, for a (1,7) code, the Shannon capacity, C(1,7), has a value of 0.67929. This means that a (1,7) code cannot have a rate larger than 0.67929. The practical implementation of codes requires that the rate be a rational fraction, and to date the above (1,7) code has a rate 2/3. This rate of 2/3 is slightly less than the Shannon capacity of 0.67929, and the code is therefore a highly efficient one. To achieve the 2/3 rate, 2 unconstrained data bits are mapped into 3 constrained encoded bits.

(1,7) codes having a rate of 2/3 and means for implementing associated encoders and decoders are known in the art. U.S. Patent No. 4,413,251 entitled "Method and Apparatus for Generating A Noiseless Sliding Block Code for a (1,7) Channel with Rate 2/3", issued in the names of Adler et al., discloses an encoder which is a finite-state machine having 5 internal states. U.S. Patent No. 4,488,142

entitled "Apparatus for Encoding Unconstrained Data onto a (1,7) Format with Rate 2/3", issued in the name of Franaszek discloses an encoder having 8 internal states.

However, a demand exists for even more efficient codes so that, for example, the information density on a recording medium or over a transmission line can be increased.

SUMMARY OF THE INVENTION

In the converting method and apparatus according to the present invention, m-bit information words are converted into n-bit code words at a rate greater than 2/3. Consequently, the same amount of information can be recorded in less space, and information density increased.

In the present invention, n-bit code words are divided into a first type and a second type, and into coding states of a first kind and a second kind such that an m-bit information word is converted into an n-bit code word of the first or second kind if the previous m-bit information word was converted into an n-bit code word of the first type and is converted into an n-bit code word of the first kind if the previous m-bit information word was converted into an n-bit code word of the second type. In one embodiment, n-bit code words of thè first type end in zero, n-bit code words of the second type end in one, n-bit code words of the first kind start with zero, and n-bit code words of the second kind start with zero or one. Furthermore, in the embodiments according to the present invention, the n-bit code words satisfy a dk-constraint of (1,k) such that a minimum of 1 zero and a maximum of k zeros falls between consecutive ones.

In other embodiments of the present invention, the coding device and method according to the present invention are employed to record information on a recording medium and create a recording medium according to the present invention.

In still other embodiments of the present invention, the coding device and method according to the present invention are further employed to transmit information.

In the decoding method and apparatus according to the present invention, n-bit code words created according to the coding method and apparatus are decoded into m-bit information words. The decoding involves determining the state of a next n-bit code word, and based on the state determination, the current n-bit code word is converted into an m-bit information word.

In other embodiments of the present invention, the decoding device and method according to the present invention are employed to reproduce information from a recording medium.

In still other embodiments of the present invention, the decoding device and method according to the present invention are employed to receive information transmitted over a medium.

BRIEF DESCRIPTION OF THE DRAWINGS

The present invention will become more fully understood from the detailed description given herein below and the accompanying drawings which are given by way of illustration only, wherein like reference numerals designate corresponding parts in the various drawings, and wherein:

FIGURE 1 tabulates the Shannon capacity C(d,k) for d=1 versus k;

FIGURE 2 shows an example of how the code words in the various subgroups are allocated in to the various states in the first embodiment;

FIGURE 3 shows an embodiment for a coding device according to the invention;

FIGURES 4A-4H show a complete translation table according to the first embodiment for converting 9-bit information words into 13-bit code words;

FIGURE 5 illustrates the conversion of a series of information words into a series of code words using the translation table of FIGURES 4A-4H;

FIGURE 6 illustrates an embodiment of a recording device according to the present invention;

FIGURE 7 illustrates a recording medium and modulated signal according to the present invention;

FIGURE 8 illustrates a transmission device according to the present invention;

FIGURE 9 illustrates a decoding device according to the present invention;

FIGURE 10 illustrates a reproducing device according to the present invention;

FIGURE 11 illustrates a receiving device according to the present invention;

FIGURE 12 shows an example of how the code words in the various subgroups are allocated in to the various states in the second embodiment;

FIGURES 13A-13C show the beginning, middle and end portions of a translation table according to the second embodiment for converting 9-bit information words into 13-bit code words

FIGURE 14 shows an example of how the code words in the various subgroups are allocated in to the various states in the third embodiment;

FIGURES 15A-15C show the beginning, middle and end portions of a translation table according to the third embodiment for converting 11-bit information words into 16-bit code words

FIGURE 16 shows an example of how the code words in the various subgroups are allocated in to the various states in the fourth embodiment; and

FIGURES 17A-17C show the beginning, middle and end portions of a translation table according to the fourth embodiment for converting 13-bit information words into 19-bit code words.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

The general coding method according to the present invention will be described followed by a specific first embodiment of the coding method. Next, the

general decoding method according to the present invention will be described in the context of the first embodiment. The various apparatuses according to the present invention will then be described. Specifically, the coding device, recording device, transmission device, decoding device, reproducing device and receiving device according to the present invention will be described. Afterwards, additional coding embodiments according to the present invention will be described.

CODING METHOD

According to the present invention, an m-bit information word is converted into an n-bit code word such that the rate of m/n is greater than 2/3. The code words are divided into first and second types wherein the first type includes code words ending with "0" and the second type includes code words ending with "1." As a result, the code words of the first type are divided into two subgroups E00 and E10, and code words of the second type are divided into two subgroups E01 and E11. Code word subgroup E00 includes code words that start with "0" and end with "0", code word subgroup E01 includes code words that start with "0" and end with "1", code word subgroup E10 includes code words that start with "1" and end with "0", and code word subgroup E11 includes code words that start with "1" and end with "1".

The code words are also divided into at least one state of a first kind and at least one state of a second kind. States of the first kind include code words that only start with "0," and states of the second kind include code words that start with either "0" or "1."

CODING METHOD ACCORDING TO A FIRST EMBODIMENT

In a first preferred embodiment of the present invention, 9-bit information words are converted into 13-bit code words. The code words satisfy a (d,k) constraint of (1,k), and are divided into 3 states of the first kind and 2 states of the second kind (a total of 5 states). In order to reduce the k-constraint, three code words, namely, "0000000000000", "0000000000001", and "0000000000010" are

barred from the encoding tables. An enumeration of code words shows there are 231 code words in subgroup E00, 144 code words in subgroup E10, 143 code words in subgroup E01, and 89 code words in subgroup E11.

To perform encoding, each 13-bit code word in each state is associated with a coding state direction. The state direction indicates the next state from which to select a code word in the encoding process. The state directions are assigned to code words such that code words that end with a "0" (i.e. code words in subgroups E10 and E00) have associated state directions that indicate any of the r=5 states, while code words that end with a "1" (i.e., code words in subgroups E01 and E11) have associated state directions that only indicate one of the states of the first kind. This ensures that the d=1 constraint will be satisfied; namely, after a code word ending in "1", the next code word will start with "0".

Furthermore, while, as explained in more detail below, the same code word can be assigned to different information words in the same state, different states cannot include the same code word. In particular code words in subgroups E10 and E00 can be assigned 5 times to different information words within one state, while code words in subgroups E11 and E01 can be assigned 3 times to different information words within one state. As there are 231 code words in subgroup E00 and 144 code words in subgroup E10, there are 1875 (5*(231+144)) "code word – state direction" combinations for code words of the first type. There are 143 code words in subgroup E01 and 89 code words in E11, so that there are 696 (3*(143+89)) "code word – state direction" combinations for code words of the second type. In total 1875+696=2571 "code word - state direction" combinations exist.

For m-bit information words, there are a total of 2^m possible information words. So, for 9-bit information words, $2^9 = 512$ information words exist. Because there are five states in this encoding embodiment, 5 times 512 = 2561 of the "code word - state direction" combinations are needed. This leaves 2571-2561 = 10 remaining combinations.

The available code words in the various subgroups are distributed over the states of the first and second kind in compliance with the restrictions discussed above. FIGURE 2 shows an example of how the code words in the various subgroups are allocated in this embodiment to the various states. As shown in FIGURE 2, in this example, states 1, 2, and 3 are states of the first kind and states 4 and 5 are states of the second kind. Taking the subgroup E00 of size 230 as an example, subgroup E00 has 76 code words in each of states 1, 2, and 3 plus 1 code word in each of states 4 and 5. And, taking state 1 as an example, in state 1 the number of "code word – state direction" combinations is 5x76+3x44=512, which means that 9-bit information words can be assigned. Remember, each code word of the first type can be assigned any one of the five different states as a state directions, and therefore used five time within a state; while each code word of the second type can only be assigned one of the three states of the first kind as a state direction because of the d=1 restriction, and therefore used three times within a state.

It can be verified that from any of the r=5 coding states shown in FIGURE 2 there at least 512 information words that can be assigned to code words, which is enough to accommodate 9-bit information words. In the manner described above any random series of 9-bit information words can be uniquely converted to a series of code words.

FIGURES 4A-4H show a complete translation table according to this embodiment for converting 9-bit information words into 13-bit code words. Included in the translation table of FIGURES 4A-4H are the state direction assigned to each code word. Specifically, in FIGURES 4A-4H, the first column shows the decimal notation of the information words in the second column. The third, fifth, seventh, ninth and eleventh columns show the code words (also referred to in the art as channel bits) assigned to the information words in states 1, 2, 3, 4 and 5, respectively. The fourth, sixth, eighth, tenth and twelfth columns show by way of the respective digits 1, 2, 3, 4 and 5 the state direction of the

associated code words in the third, fifth, seventh, ninth and eleventh columns, respectively.

The conversion of a series of information words into a series of code words will be further explained with reference to FIGURE 5. The first column of FIGURE 5 shows from top to bottom a series of successive 9-bit information words, and the second column shows in parenthesis the decimal values of these information words. The third column "state" is the coding state that is to be used for the conversion of the information word. The "state" is laid down when the preceding code word was delivered (i.e., the state direction of the preceding code word). The fourth column "code words" includes the code words assigned to the information words according to the translation table of FIGURES 4A-H. The fifth column "next state" is the state direction associated with the code word in the fourth column and is also determined according to the translation table of FIGURES 4A-H.

The first word from the series of information words shown in the first column of FIGURE 5 has a word value of "1" in decimal notation. Let us assume that the coding state is state 1 (S1) when the conversion of the series of information words is initiated. Therefore the first word is translated into code word "0000000000100" according to the state 1 set of code words from the translation table. At the same time the next state becomes state 2 (S2) because the state direction assigned to code word "0000000000100" representing decimal value 1 in state 1 is state 2. This means that the next information word (decimal value "3") is going to be translated using the code words in state 2. Consequently, the next information word, having a decimal value of "3", is translated into code word "0001010001010". Similar to the manner described above, the information words having the decimal values "5", "12" and "19" are converted.

DECODING METHOD

Hereinafter, decoding of n-bit code words (in this example 13-bit words) received from a recording medium will be further explained with reference to

FIGURES 4A-4H. For th purposes of description, assume that th word values of a series of successive code words received from, for example, a recording medium are "0000000000100", "0001010001010", "0101001001001". From th translation table of FIGURES 4A-4H, it is found that the first code word "0000000000100" is assigned to the information words "0", "1", "2", "3" and "4" and state directions 1, 2, 3, 4 and 5, respectively. The next code word value is "0001010001010", and belongs to the set of code words in state 2. This means that the first code word "0000000000100" had a state direction of 2. The first code word "0000000000100" with a state direction of 2 represents the information word having a decimal value of "1". Therefore, it is determined that the first code word represents information word "000000001" having a decimal value of "1".

Furthermore, the third code word "0101001001001" is a member of state 4. Therefore, it is determined in the same manner as above that the second code word "0001010001010" represents the information word having the decimal value "3". In the same manner other code words can be decoded. It is noted that both the current code word and the next code words are observed to decode the current code word into a unique information word.

CODING DEVICE

FIGURE 3 shows an embodiment for a coding device 124 according to the invention. The coding device 124 converts m-bit information words into n-bit code words, where the number of different coding states r is represented by s bits. For example, when the number of coding states r = 5, s equals 3. As shown, the coding device 124 includes a converter 50 for converting (m+s) binary input signals to (n+s) binary output signals. In a preferred embodiment, the converter 50 includes a read only memory (ROM) storing a translation table according to at least one embodiment of the present invention and address circuitry for addressing the translation table based on the m+s binary input signals. However, instead of a ROM, the converter 50 can include a combinatorial logic circuit

producing the same results as the translation table according to at least one embodiment of the present invention.

From the inputs of th converter 50, m inputs are connected to a first bus 51 for receiving m-bit information words. From the outputs of the converter 50, n outputs are connected to a second bus 52 for delivering n-bit code words. Furthermore, s inputs are connected to an s-bit third bus 53 for receiving a state word that indicates the instantaneous coding state. The state word is delivered by a buffer memory 54 including, for example, s flip-flops. The buffer memory 54 has s inputs connected to a fourth bus 55 for receiving a state direction to be loaded into the buffer memory 54 as the state word. For delivering the state directions to be loaded in the buffer memory 54, the s outputs of the converter 50 are used.

The second bus 52 is connected to the parallel inputs of a parallel-to-serial converter 56, which converts the code words received over the second bus 52 to a serial bit string. A signal line 57 supplies the serial bit string to a modulator circuit 58, which converts the bit string into a modulated signal. The modulated signal is then delivered over a line 60. The modulator circuit 58 is any well-known circuit for converting binary data into a modulated signal such as a modula-2 integrator.

For the purposes of synchronizing the operation of the coding device, the coding device includes a clock generating circuit (not shown) of a customary type for generating clock signals for controlling timing of, for example, the parallel/serial converter 58 and the loading of the buffer memory 54.

In operation, the converter 50 receives m-bit information words and an s-bit state word from the first bus 51 and the third bus 53, respectively. The s-bit state word indicates the state in the translation table to use in converting the m-bit information word. Accordingly, based on the value of the m-bit information word, the n-bit code word is determined from the code words in the state identified by the s-bit state word. Also, the state direction associated with the n-bit code word is determined. The state direction, namely, the value thereof is converted into an s-bit binary word; or alternatively, the state directions are stored in the translation

table as s-bit binary words. The converter 50 outputs the n-bit code word on the second bus 52, and outputs the s-bit state direction on fourth bus 55. The buffer memory 54 stores the s-bit state direction as a state word, and supplies the s-bit state word to the converter 50 over the third bus 53 in synchronization with the receipt of the next m-bit information word by the converter 50. This synchronization is produced based on the clock signals discussed above in any well-known manner.

The n-bit code words on the second bus 52 are converted to serial data by the parallel/serial converter 56, and then the serial data is converted into a modulated signal by the modulator 58.

The modulated signal may then undergo further processing for recordation or transmission.

RECORDING DEVICE

FIGURE 6 shows a recording device for recording information that includes the coding device 124 according to the present invention as shown in FIGURE 3. As shown in FIGURE 6, m-bit information is converted into a modulated signal through the coding device 124. The modulated signal produced by the coding device 124 is delivered to a control circuit 123. The control circuit 123 may be any conventional control circuit for controlling an optical pick-up or laser diode 122 in response to the modulated signal applied to the control circuit 123 so that a pattern of marks corresponding to the modulated signal are recorded on the recording medium 110.

FIGURE 7 shows by way of example, a recording medium 110 according to the invention. The recording medium 110 shown is a read-only memory (ROM) type optical disc. However, the recording medium 110 of the present invention is not limited to a ROM type optical disk, but could be any type of optical disk such as a write-once read-many (WORM) optical disk, random accessible memory (RAM) optical disk, etc. Further, the recording medium 110 is not limited to being

an optical disk, but could be any typ of recording medium such as a magn tic disk, a magneto-optical disk, a memory card, magnetic tape, etc.

As shown in FIGURE 7, the recording medium 110 according to one embodiment of the present invention includes information patterns arranged in tracks 111 . Specifically, FIGURE 7 shows an enlarged view of a track 111 along a direction 114 of the track 111. As shown, the track 111 includes pit regions 112 and non-pit regions 113. Generally, the pit and non-pit regions 112 and 113 represent constant signal regions of the modulated signal 115 (zeros in the code words) and the transitions between pit and non-pit regions represent logic state transitions in the modulated signal 115 (ones in the code words).

As discussed above, the recording medium 110 may be obtained by first generating the modulated signal and then recording the modulated signal on the recording medium 110. Alternatively, if the recording medium is an optical disc, the recording medium 110 can also be obtained with well-known mastering and replica techniques.

TRANSMISSION DEVICE

FIGURE 8 shows a transmission device for transmitting information that includes the coding device 124 according to the present invention as shown in FIGURE 3. As shown in FIGURE 8, m-bit information words are converted into a modulated signal through the coding device 124. A transmitter 150 then further processes the modulated signal, to convert the modulated signal into a form for transmission depending on the communication system to which the transmitter belongs, and transmits the converted modulated signal over a transmission medium such as air (or space), optical fiber, cable, a conductor, etc.

DECODING DEVICE

FIGURE 9 illustrates a decoder according to the present invention. The decoder performs the reverse process of the converter of FIGURE 3 and converts n-bit code words of the present invention into m-bit information words. As shown,

the decoder 100 includes a first look-up table (LUT) 102 and a second LUT 104. The first and second LUTs 102 and 104 store the translation tabl used to create the n-bit code words being decoded. Where K refers to time, the first LUT 102 receives the (K+1)th n-bit code word and the second LUT 104 receives the output of the first LUT 102 and the Kth n-bit code word. Accordingly, the decoder 100 operates as a sliding block decoder. At every block time instant the decoder 100 decodes one n-bit code word into one m-bit information word and proceeds with the next n-bit code word in the serial data (also referred to as the channel bit stream).

In operation, the first LUT 102 determines the state of the (K+1)th code word from the stored translation table, and outputs the state to the second LUT 104. So the output of the first LUT 102 is a binary number in the range of 1, 2,..., r (where r denotes the number of states in the translation table). The second LUT 104 determines the possible m-bit information words associated with Kth code word from the Kth code word using the stored translation table, and then determines the specific one of the possible m-bit information words being represented by the n-bit code word using the state information from the first LUT 102 and the stored translation table.

For the purposes of further explanation only, assume the n-bit code words are 13-bit code words produced using the translation table of FIGURES 4A-4H. Then, referring to FIGURE 5, if the (K+1)th 13-bit code word is "0001010001010" the first LUT 102 determines the state as state 2. Furthermore, if the Kth 13-bit code word is "0000000000100", then the second LUT 104 determines that the Kth 13-bit code word represents one of the 9-bit information words having a decimal value of 0, 1, 2, 3 or 4. And, because the next state or state direction of state 2 is supplied by the first LUT 102, the second LUT 104 determines that the Kth 13-bit code word represents the 9-bit information word having a decimal value of 1 because the 13-bit code word "0000000000100" associated with a state direction of 2 represents the 9-bit information word having a decimal value of 1.

REPRODUCING DEVICE

FIGURE 10 illustrates a reproducing device that includes the decoder 100 according to the present invention as shown in FIGURE 9. As shown, the reading device includes an optical pick-up 122 of a conventional type for reading a recording medium 110 according to the invention. The recording medium 110 may be any type of recording medium such as discussed previously. The optical pick-up 122 produces an analog read signal modulated according to the information pattern on the recording medium 110. A detection circuit 125 converts this read signal in conventional fashion into a binary signal of the form acceptable to the decoder 100. The decoder 100 decodes the binary signal to obtain the m-bit information words.

RECEIVING DEVICE

FIGURE 11 illustrates a receiving device that includes the decoder 100 according to the present invention as shown in FIGURE 9. As shown, the receiving device includes a receiver 160 for receiving a signal transmitted over a medium such as air (or space), optical fiber, cable, a conductor, etc. The receiver 160 converts the received signal into a binary signal of the form acceptable to the decoder 100. The decoder 100 decodes the binary signal to obtain the m-bit information words.

CODING METHOD ACCORDING TO A SECOND EMBODIMENT

FIGURES 12 and 13A-13C illustrate another embodiment of the present invention. According to this embodiment, the greater than 2/3 rate is achieved by converting 9-bit information words into 13-bit code words; wherein the number of coding states r equals 13, and 8 of the coding states are coding states of the first kind and 5 of the coding states are coding states of the second kind. Also, the code words satisfy a (d,k) constraint of (1,k). FIGURE 12 corresponds to FIGURE 2 of the first embodiment, and illustrates the division of code words among the states in this second embodiment.

As described above, cod words that end with a "0", i.e. code words in subgroups E00 and E10, are allowed to enter any of the r=13 states, while code words that end with a "1" i. . code words in subgroups E01 and E11, may only enter the states of the first kind(State 1 to State 8).

Therefore, code words in subgroups E00 and E10 can be assigned 13 times to different information words, while code words in subgroups E01 and E11 can be assigned 8 times to different information words. Referring to FIGURE 12, subgroup E00 has 24 code words in state 1 and the subgroup E01 has 25 code words in state 1. So the number of "code words - state direction" combinations is (13x24)+(8x25)=512, which means that 9-bit information words can be assigned. It can be verified that from any of the r=13 coding states there at least 512 information words that can be assigned to code words, which is enough to accommodate 9-bit information words.

FIGURES 13A-13C illustrate the beginning, middle and end portions of the translation table for this second embodiment in the same fashion that FIGURES 4A-4H illustrated the translation table for the first embodiment.

CODING METHOD ACCORDING TO A THIRD EMBODIMENT

FIGURES 14 and 15A-15C illustrate another embodiment of the present invention. According to this embodiment, the greater than 2/3 rate is achieved by converting 11-bit information words into 16-bit code words; wherein the number of coding states r equals 13, and 8 of the coding states are coding states of the first kind and 5 of the coding states are coding states of the second kind. Also, the code words satisfy a (d,k) constraint of (1,k). FIGURE 14 corresponds to FIGURE 2 of the first embodiment, and illustrates the division of code words among the states in this third embodiment. It can be verified that from any of the r=13 coding states there at least 2048 information words that can be assigned to code words, which is enough to accommodate 11-bit information words.

FIGURES 15A-15C illustrate the beginning, middle and end portions of the translation table for the third embodiment in the same fashion that FIGURES 4A-4H illustrated the translation table for the first embodiment.

CODING METHOD ACCORDING TO A FOURTH EMBODIMENT

FIGURES 16 and 17A-17C illustrate another embodiment of the present invention. According to this embodiment, the greater than 2/3 rate is achieved by converting 13-bit information words into 19-bit code words; wherein the number of coding states r equals 5, and 3 of the coding states are coding states of the first kind and 2 of the coding states are coding states of the second kind. Also, the code words satisfy a (d,k) constraint of (1,k). FIGURE 16 corresponds to FIGURE 2 of the first embodiment, and illustrates the division of code words among the states in this fourth embodiment. It can be verified that from any of the r=5 coding states there at least 8192 information words that can be assigned to code words, which is enough to accommodate 13-bit information words.

FIGURES 17A-17C illustrate the beginning, middle and end portions the translation table for the fourth embodiment in the same fashion that FIGURES 4A-4H illustrated the translation table for the first embodiment.

The invention has been described in detail with particular reference to preferred embodiments thereof, but it will be understood that variations and modifications can be effected within the spirit and scope of the invention.